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Introduction: from the British Tertiary into the future – modern perspectives on the British Palaeogene and North Atlantic Igneous provinces

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The study of volcanic rocks and igneous centres has long been a classic part of geological research. Despite the lack of active volcanism, the British Isles have been a key centre for the study of igneous rocks ever since ancient lava flows and excavated igneous centres were recognized there in the 18th century (Hutton, 1788). This led to some of the earliest detailed studies of petrology. The starting point for many of these studies was the British Palaeogene Igneous Province (BPIP; formerly known as the 'British Tertiary' (Judd, 1889), and still recognized by this name by many geologists around the globe). This collection of lavas, volcanic centres and sill/dyke swarms covers much of the west of Scotland and the Antrim plateau of Northern Ireland, and together with similar rocks in the Faroe Islands, Iceland and Greenland forms a world-class Large Igneous Province. This North Atlantic Igneous Province (NAIP) began to form through continental rifting above a mantle plume at *c.* 60 Ma, and subsequently evolved as North America separated from Europe, creating the North Atlantic Ocean.

During a recent field workshop entitled 'Golden Rum' (see Goodenough *et al.* 2008), as part of the bicentenary celebrations of the Geological Society of London, some 30 earth scientists gathered for a field workshop held on the isles of Rum and Skye. Field trips visited some classic igneous localities, celebrating the work of many great geoscientists past and present. Talks were presented at the Aros Centre on the Isle of Skye, outlining some of the current research on the province, and highlighting some exciting new results. This collection of papers is derived from talks presented during that meeting and represents a snapshot of some of the current areas of interest in the NAIP, focusing particularly on the British Palaeogene. Clearly this is not an all-encompassing volume covering every area of research, but it provides a look at the depth and breadth of modern studies in the NAIP, which build on the solid foundations of over two centuries of work in the region.

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1. The bigger picture – the British Palaeogene and North Atlantic Igneous Provinces

The North Atlantic Igneous Province (NAIP) is a classic Large Igneous Province (LIP), and research in this area has fuelled debates on such issues as the origins of large outpourings of flood basalts, the relationships of the intrusive and extrusive parts of igneous centres, the timescales of magmatism, and the presence or absence of mantle plumes. The NAIP is not only laterally extensive (over thousands of kilometres), but formed over a somewhat protracted period of time when compared to some other LIPs. As such, it can be an informative area to test our understanding of the formation of such provinces, through continental rifting and possible mantle plume involvement. Hansen *et al.* (this volume) provide a review which considers the formation of the NAIP in the context of global plate reorganizations, and lithospheric extension across old orogenic fronts and suture zones. They show that magmatism in the NAIP was controlled by a combination of the underlying complex tectonic picture, and mantle processes such as local or regional scale upwellings prior to and during the Early Eocene rifting. This approach may help to explain the presence of more localized igneous centre components of the NAIP, as well as the rather heterogenous distribution of igneous products over a large but geographically constrained area.

The formation of such a complex construction of igneous centres and associated flood basalts over a protracted time period (*c.* 62–54 Ma, e.g. Saunders *et al.* 1997; Jerram & Widdowson, 2005) provides a large amount of material to be eroded. Brown, Holohan & Bell (this volume) focus on this somewhat poorly studied part of the province's evolution. They review the erosion of the igneous centres and associated lava fields of the BPIP, and identify the sedimentary responses to four broadly chronological stages in the history of the

BPIP volcanoes: the development of the lava fields; early intrusion-induced uplift; caldera collapse; and post-volcano denudation and exhumation of central complexes. The dynamic landscape that developed during these times consisted of alluvial fans, braided rivers, lakes and swamps. Into these environments, and during key stages in the development of the igneous centres, large volcanoes provided material through catastrophic mass wasting and/or caldera collapse events.

Another noteworthy area of research in the NAIP stems from a different driving factor: exploration of offshore regions where flood basalts cover sedimentary basins that may contain recoverable hydrocarbons. Offshore areas beneath flood basalt cover are notoriously difficult to image and therefore increased understanding of the internal architecture of the flood basalt sequences may assist in dealing with the 'sub-basalt imaging' problem, as well as providing valuable information from which good models and strategies for exploration can be tested. The contribution from Jerram *et al.* (this volume) looks at the internal architecture of the offshore region of the Faroe–Shetland basin to understand the volcanic facies there. Onshore analogues for known volcanic facies such as tubular flows, compound flows and hyaloclastites, which are preserved in onshore settings such as the Faroe Islands, can be used to interpret the internal structure of the offshore lava sequence. The mapping of these facies types provides information about significant seaways that were present around the onset of flood volcanism in the Faroe–Shetland basin, and when reasonable velocity models and gravity data are combined, better-constrained models for the sub-basalt geology can be produced.

2. A classic closer view – understanding the igneous centres

Focusing in a little, the NAIP (and in particular the British part) is famous for its well-exposed lava fields and igneous centres (e.g. Emeleus & Bell, 2005). Significant recent research has concentrated on the great natural laboratory of the Isle of Rum (Emeleus, 1997), and the other contributions in this issue discuss recent work in the Rum Central Complex, using the latest ideas and techniques to revisit its classic layered intrusion and associated pyroclastic deposits.

Nicoll *et al.* (this volume) have studied the episode of early and voluminous felsic magmatism which preceded the formation of the mafic and ultramafic layered suite in the Rum Central Complex. This magmatic phase, which was associated with caldera formation, comprises a range of volcaniclastic breccias, felsic intrusives, and ignimbrites and tuffs produced by explosive eruptions. The felsic magmas are largely the product of crustal melting (Troll, Donaldson & Emeleus, 2004; Meyer *et al.* this volume) but there is little direct evidence of the earliest stage of anatexis, and even less is known about the heat source that would have been required to melt enough crust to produce such a large amount of felsic magma. Nicoll *et al.* present evidence for early mafic intrusions that triggered anatexis and the large-scale generation of felsic magmas, which ultimately led to explosive felsic volcanism on Rum. They describe the enigmatic and distinctive Am Màm intrusion breccia, revise its emplacement history and demonstrate that it contains entrained clasts of country rock, early gabbro and peridotite, which record a pre-caldera episode of contact metamorphism and anatexis at depth. These findings provide a unique record of early anatectic processes and the mafic magmas originally responsible for driving felsic magmatism on Rum, possibly providing a key to investigating the origin of felsic melts elsewhere in the North Atlantic Igneous Province.

Meyer *et al.* (this volume) build on the work of Nicoll *et al.* (this volume), using geochemical and isotopic data to study the petrogenesis of the rhyodacitic and dacitic rocks of the early magmatic phase in the Rum Central Complex. They show that the rhyodacites appear to be formed by large degrees of melting of Lewisian amphibolite-facies gneiss, whereas the dacitic volcanic rocks and the early gabbros are mixtures of crustal melts and primary mantle-derived magmas. Late-stage picrites are considered to be close analogues for the primitive mantle-derived melts that caused crustal anatexis and for the parental magma of the Layered Suite. The rhyodacites have noticeably lower $^{87}Sr/^{86}Sr$ ratios, lower Rb and especially lower Cs concentrations than would be expected for partial melts from Lewisian amphibolite gneisses that crop out as uplifted blocks and inclusions in the Rum Central Complex. These findings are interpreted as indications for a Cs–Rb depletion event that affected the actual amphibolite-facies parent rocks at mid-crustal depths prior to the Palaeogene, possibly during the Caledonian orogeny.

Although high-grade granulite-facies crustal rocks are generally considered to be present beneath Rum, significant contamination from this source has not been recognized either in the felsic magmas (Meyer *et al.* this volume) or in the parent magmas of the ultrabasic Layered Suite (Palacz & Tait, 1985). The processes by which mantle-derived magmas interacted with continental crust under the Isle of Rum must have differed from those operating under the Isle of Skye, where granulite-facies gneiss appears to have been an important crustal contaminant in the lavas (Font *et al.* 2008).

Holohan *et al.* (this volume) have studied the physical volcanology of the early magmatic phase on Rum. Although it was long thought that the evolution of collapse caldera volcanoes begins with a large-magnitude uplift ('tumescence') of country rocks upon initial intrusion of a large pre-caldera magma body, evidence for such pre-collapse uplift has been elusive or absent in recent surveys of a range of volcanoes. This has sown doubt as to whether pre-caldera tumescence is important enough to be recorded in significant geological structures (Lipman, 1997). However, the Northern Marginal Zone of the Rum Central Complex has been shown to contain exceptional evidence for intrusion-induced uplift prior to caldera collapse (Troll, Emeleus & Donaldson, 2000). Holohan *et al.* have investigated the lithological characteristics and field relationships of equivalent rocks within the remote, extensive, and more deeply dissected Southern Mountains Zone, allowing further constraint of the processes during pre-caldera tumescence. They provide detailed evidence to underpin reinterpretation of intrusive rhyodacite sills and subterranean explosion breccias as extrusive ignimbrites and sedimentary mass-movement deposits, respectively. In terms of geological processes, this new evidence refines our understanding of a rarely preserved sequence of rocks that record volcano-sedimentary responses to intrusion-induced uplift and caldera collapse.

Early felsic magmatism on Rum included intrusive bodies as well as caldera-fill material. The Western Granite on Rum is the largest of several granitic bodies around the margin of the Rum Central Complex, all of which are interpreted as part of the early felsic updoming and caldera collapse episode. Petronis *et al.* (this volume) report palaeomagnetic and anisotropy of magnetic susceptibility (AMS) data that bear on the emplacement and deformation of the Western Granite. The data indicate a component of outward tilting, recorded in the Western Granite, which did not affect the younger Layered Suite. This suggests that emplacement of the ultrabasic magmas at a shallow crustal level caused significant distortion and local remobilization of the country rocks; roof uplift and associated tilt of the Western Granite probably occurred to make space for mafic magma emplacement. On the basis of magnetic fabric magnitude and susceptibility parameters, Petronis *et al.* recognize two principal groupings in the Western Granite AMS dataset, and suggest that these record sub-vertical magma ascent near a feeder conduit in the east, with sub-horizontal flow westwards away from the conduit forming a sheet-like intrusion. The magnetic foliations, together with deformation of the country rock, suggest that doming also accompanied emplacement of the early granitic magma.

Perhaps the most widely known parts of the Rum Central Complex are its classic mafic to ultramafic layered intrusions. The Eastern Layered Intrusion has long been recognized as having been built up from a number of discrete chamber replenishment events. The classical idea of Brown (1956) is that there were 16 such events, each corresponding to a single macro-unit. Holness & Winpenny (this volume) have carried out a detailed investigation of the Unit 12 allivalite, using previously published isotope data together with new textural and geochemical data, and they demonstrate that this 16 m thick body records more than half a dozen replenishment events, at least one of which triggered an eruption. The replenishing magmas varied from picrite to basalt and had highly variable degrees of interaction with crustal material before arriving in the shallow-level chamber. At its thinnest, the sill-like chamber may have been only a few tens of metres thick. Holness & Winpenny propose that the idea of a large magma chamber, periodically refilled with large amounts of picrite, needs to be revised towards a model in which a shallow chamber was fed by small batches of highly variable magma, probably sourced from a series of deeper chambers.

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References

BROWN, G. M. 1956. The layered ultrabasic rocks of Rhum, Inner Hebrides. *Philosophical Transactions of the Royal Society of London, Series B* **240**, 1–54.

BROWN, D. J., HOLOHAN, E. P. & BELL, B. R. 2009. Sedimentary and volcano-tectonic processes in the British Paleocene Igneous Province: a review. *Geological Magazine* **146**, 326–52.

EMELEUS, C. H. & BELL, B. R. 2005. *British Regional Geology: the Palaeogene Volcanic districts of Scotland* (4th ed.). Keyworth: British Geological Survey, 214 pp.

EMELEUS, C. H. 1997. *Geology of Rum and the adjacent islands: Memoir for 1:50 000 Geological Sheet 60 (Scotland) of the British Geological Survey*. London: The Stationery Office, 170 pp.

FONT, L., DAVIDSON, J. P., PEARSON, D. G., NOWELL, G. M., JERRAM, D. A. & OTTLEY, C. J. 2008. Sr and Pb isotope micro-analysis of plagioclase crystals from Skye lavas: an insight into open-system processes in a flood basalt province. *Journal of Petrology*, **49**, 1449–71.

GOODENOUGH, K. M., EMELEUS, C. H., JERRAM, D. A. & TROLL, V. R. 2008. Golden Rum: understanding the forbidden isle. *Geoscientist* **18**, Part 3, 000–00.

HANSEN, J., JERRAM, D. A., MCCAFFREY, K. & PASSEY, S. R. 2009. The onset of the North Atlantic Igneous Province in a rifting perspective. *Geological Magazine* **146**, 309–25.

HOLNESS, M. B. & WINPENNY, B. 2009. The Unit 12 allivalite, Eastern Layered Intrusion, Isle of Rum: a textural and geochemical study of an open-system magma chamber. *Geological Magazine* **146**, 437–50.

HOLOHAN, E. P., TROLL, V. R., ERRINGTON, M., DONALDSON, C. H., NICOLL, G. R. & EMELEUS, C. H. 2009. The Southern Mountains Zone, Isle of Rum, Scotland: volcanic and sedimentary processes upon an uplifted and subsided magma chamber roof. *Geological Magazine* **146**, 400–18.

HUTTON, J. 1788. Theory of the Earth: or an investigation of the laws observable in the composition, dissolution and restoration of the land upon the globe. *Transactions of the Royal Society of Edinburgh* **1**, 209–304.

Jerram, D. A., Single, R. T., Hobbs, R. W. & Nelson, C. E. 2009. Understanding the offshore flood basalt sequence using onshore volcanic facies analogues: an example from the Faroe–Shetland basin. *Geological Magazine* **146**, 353–67.

Jerram, D. A. & Widdowson, M. 2005. The anatomy of Continental Flood Basalt Provinces: geological constraints on the processes and products of flood volcanism. *Lithos* **79**, 385–405.

Judd, J. W. 1889. The Tertiary volcanoes of the Western Isles of Scotland. *Quarterly Journal of the Geological Society of London* **45**, 187–219.

Lipman, P. W. 1997. Subsidence of ash-flow calderas: relation to caldera size and magma-chamber geometry. *Bulletin of Volcanology* **59**, 198–218.

Meyer, R., Nicoll, G. R., Hertogen, J., Troll, V. R., Ellam, R. M. & Emeleus, C. H. 2009. Trace element and isotope constraints on crustal anatexis by upwelling mantle melts in the North Atlantic Igneous Province: an example from the Isle of Rum, NW Scotland. *Geological Magazine* **146**, 382–99.

Nicoll, G. R., Holness, M. B., Troll, V. R., Donaldson, C. H., Holohan, E. P., Emeleus, C. H. & Chew, D. 2009. Early mafic magmatism and crustal anatexis on the Isle of Rum: evidence from the Am Màm intrusion breccia. *Geological Magazine* **146**, 368–81.

Palacz, Z. A. & Tait, S. R. 1985. Isotopic and geochemical investigation of Unit 10 from Eastern Layered Series of the Rhum Intrusion, Northwest Scotland. *Geological Magazine* **122**, 485–90.

Petronis, M. S., O'Driscoll, B., Troll, V. R., Emeleus, C. H. & Geissman, J. W. 2009. Palaeomagnetic and anisotropy of magnetic susceptibility data bearing on the emplacement of the Western Granite, Isle of Rum, NW Scotland. *Geological Magazine* **146**, 419–36.

Saunders, A. D., Fitton, J. G., Kerr, A. C., Norry, M. J. & Kent, R. W. 1997. The North Atlantic Igneous Province. *Geophysical Monographs* **100**, 45–93.

Troll, V. R., Emeleus, C. H. & Donaldson, C. H. 2000. Caldera Formation in the Rum Central Igneous Complex, Scotland. *Bulletin of Volcanology* **62**, 301–17.

Troll, V. R., Donaldson, C. H. & Emeleus, C. H. 2004. Pre-eruptive magma mixing in ash-flow deposits of the Tertiary Rum Igneous Centre, Scotland. *Contributions to Mineralogy and Petrology* **147**, 722–39.